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ABSTRACT

The four papers in this collection were commissioned by the Science Education Directorate of the National Science Foundation to assist in planning a research agenda for science education for the next ten years. A background paper by Dr. J.C.R. Licklider, "Impact of Information Technology on Education in Science and Technology," discusses the potential future impacts of technology on society, and therefore, on science education. Dr. John Seely Brown, in his paper "Fundamental Research in Technology in Science Education," discusses research trends in cognitive psychology and instructional systems, noting a shift from an emphasis on effective methods for the acquisition of facts and skills to an emphasis on the use of computers for the development of intelligent, knowledge-based instructional systems. Dr. Arthur Luehrmann's paper, "Technology in Science Education," considers the needs of schools and universities in light of the advances in educational technology. Dr. Joseph I. Lipson discusses the overall R & D effort in his paper, "Technology Program Recommendations," about the use of technology to improve science education, and summarizing the task force recommendations for a federal program for research and development in this area. (Author/JEG)

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TECHNOLOGY IN SCIENCE EDUCATION:

The Next Ten Years

Perspectives and Recommendations

July 1979

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Foreword

The computer has become a symbol that in many ways represents science and technology in the public eye. That is not surprising, since it is a versatile tool that has affected not only every field of science, but also has come rapidly into common household use.

The computer permeates many aspects of our society and impacts significantly on the daily lives of most people. Educated citizens need to know enough about computers to be able to both capitalize on and control their use. I wish to emphasize that computers offer a unique opportunity to improve the quality of education while enabling us to advance our state of knowledge in science and education. Computer technology should allow us to better prepare all of our citizens for successful lives in the real world of today and tomorrow.

F. James Rutherford

Preface

The attached papers were commissioned by the Science Education Directorate of the National Science Foundation to assist the Directorate in planning a research agenda for science education for the next ten years.

A background paper by Dr. J. C. R. Licklider, "Impact of Information Technology on Education in Science and Technology," was commissioned to discuss the potential future impacts of technology on society and, therefore, on science education. Dr. Licklider sees technology as having an enormous impact upon society but having little or no effect in the near term on education unless educators do much more than they are now doing to adapt and exploit technology. He feels that while the forces to resist the use of computers in education are currently stronger than the driving urge to use them, the needs of education for information technology are so strong that it will ultimately be adopted. Once adopted, he believes, education can play a strong role in shaping our society. However, he cautions that while the opportunities are great, the dangers of hasty, unplanned, adoption are equally great. It would be foolhardy, he concludes, to move at full speed without putting a great deal of thought and effort into an analysis of the issues and the formulation of policy.

Dr. John Seely Brown in his paper, "Fundamental Research in Technology in Science Education," discusses research trends in cognitive psychology and instructional systems. He notes a shift from an emphasis on effective methods for the acquisition of facts and skills to an emphasis on the use of computers for the development of intelligent, knowledge-based instructional systems. The predicted availability of knowledge-based systems coupled with the possibility that all knowledge will be digitally represented (rather than only in books or human minds) by the 1990's suggests many questions of interest for science education. For example, how can education take advantage of the new and revolutionary increase in new computer power? In what form should this power be delivered? How can expertise for diverse educational worlds be embedded within the computer?

Dr. Arthur Luehrmann's paper, "Technology in Science Education," considers the needs of schools and universities in light of the advances in educational technology. He treats the problems of curriculum and materials, and the potential contributions of microcomputers and other new technologies.

Dr. Joseph I. Lipson provides a paper that discusses the "Overall R&D Effort." He outlines appropriate Federal concerns in using technology to improve science education and summarizes the Task Force recommendations for a Federal program for research and development in technology in science education.

The papers are an outgrowth of several meetings and discussions that have taken place during the winter of '77 and spring of '78 to plan the research agenda for science education. The papers were presented in draft form during a three-day meeting in Washington to a distinguished group who have been involved in the use of technology in science education for a number of years. We would like to thank the following people for their participation in this process.

Dr. J. C. R. Licklider; Massachusetts Institute of Technology
Dr. John Seely Brown; Xerox, Palo Alto Research Center
Dr. Arthur W. Luehrmann; Lawrence Hall of Science, University of California-Berkeley
Dr. Joseph I. Lipson; National Science Foundation
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Dr. Judith Edwards; Northwest Regional Educational Laboratory
Dr. Harold F. O'Neil, Jr.; Army Research Institute
Dr. Robert J. Seidel; Human Resources Research Organization
Dr. Bruce Sherwood; University of Illinois/Urbana

This group presented critical response and participated in formulating the seven recommendations presented in Dr. Lipson's paper.

The papers represent, of course, the opinions of the authors and do not necessarily reflect the position of the National Science Foundation.

Dorothy K. Deringer
Andrew R. Molnar

Editors

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IMPACT OF INFORMATION TECHNOLOGY ON EDUCATION IN SCIENCE AND TECHNOLOGY

J.C.R. Licklider

INTRODUCTION

Information technology is flourishing. It is providing business, industry, the professions, and government with marvelous new tools and techniques to help them acquire, process, store, transmit, and use information. But the field of education is not taking much advantage of the new technology.

Education is not only missing a great opportunity; it is failing to discharge a crucial responsibility. The world is rapidly moving into the "information age." In order to make the transition wisely and well, the public must understand information science and technology. People must master the technology or be mastered by it.

Information technology has now advanced to a stage at which it can provide the basic information tools, techniques, and facilities required to improve education significantly. The means are now not only effective but also cost-effective. Before the technology can have its full impact on education, however, educators will have to understand it, adapt it, and apply it to meet education's needs. Let us first examine the technology itself and then look at how educators can exploit it.

ADVANCES IN INFORMATION TECHNOLOGY

Information technology has made its most dramatic advances in the area of computer hardware. In 1944, the only digital computer in operation was Harvard's Mark I, a machine based on the use of magnetic relays as logical processing and storage elements. The basic unit processing cycle of Mark I was about 10 milliseconds. The amount of information processed as a unit was about 16 bits. And the total relay-based storage capacity was about a thousand bits. The cost, if we may assume a nominal figure for what was actually an expensive laboratory-built computer, might, in limited production, have been $125,000. In 1978, one can buy, for $600 at a radio store, a computer with a basic processing cycle of about a microsecond, a word length of 8 bits, and a total "fast" storage capacity of 16,000 bits. The modern machine is about 10,000 times as fast and has about 16 times as much memory, whereas the World War II machines cost more than 200 times as much. In this comparison, as in few others, the inflation factor is negligible. The essential fact is that the cost-effectiveness of computing increased more than a million times in the interval since World War II.

The increase in cost-effectiveness over time has been approximately exponential. An analysis by Roberts[1] found that the cost-effectiveness

of 37 computers considered "large-scale" at the time they were introduced (between 1955 and 1972) increased by a factor of 1.56 per year. Within families of compatible computers, Roberts found the factor of increase per year to be "only" about 1.4. That figure corresponds to a doubling of cost-effectiveness every two years. Remaining within a family of compatible computers eliminates the need to reprogram every new machine, an attractive element of conservatism associated with the latter figure. Moreover, there are indications that the "double-every-two-years" rule has held up during the last few years and that it can be maintained through yet another decade.

LARGE-SCALE INTEGRATION OF SEMICONDUCTOR DEVICES

One component technology responsible for the dramatic increase in the cost-effectiveness of computer hardware is large-scale integration of semiconductor devices. As everyone knows who has opened a pocket calculator, the essential logic and storage component is a chip of semiconductor material about 2 mm by 3 mm. The same chip, insofar as material and size are concerned, is the basic component of most large computers and of much telecommunications switching equipment. Since the mid-1960's, there has been a race to put more and more function--more and more processing power and storage capacity--onto a single semiconductor chip. Storage capacity has increased a little faster than processing power, but both have increased so fast that a single curve describes both advances well enough. It is an exponential curve that doubles every 14 or 15 months (on an annual basis by a factor of about 1.9--a factor somewhat greater than the value for the overall advance of computer hardware technology).

Since the mid-1960's, the capability of a chip has gone up by a factor of 10,000. The cost of a chip, meanwhile, has remained approximately constant at $5 to $50. It is a rough but useful rule of thumb that new chips come onto the market at $50 and, within two or three years, sell for $5 or $10. At present, there are chips on the market that contain the entire processors of minicomputers with 16-bit word-length and others that contain 4,096 bits of memory. Applying the exponential rule leads to the expectation of 32-bit-word microprocessors and 16,384- and 65,336-bit memories in the early 1980's.

However, the large-scale integration of semiconductor devices is currently at a crux. The active elements on the chip--out of which processors and memories are made with the aid of interconnecting "wires" that also are on the chip--are now about as small as can be achieved through processes similar to etching and engraving with visible light. A small further advance can be achieved by moving from visible light to ultraviolet light--which has a somewhat shorter wavelength. To continue the exponential increase of power and capacity another five or ten years, however, it will be necessary to switch from photographic techniques that employ visible light to x-ray and electron-beam or ion-beam techniques.

Most large companies in the business, and most small ones that can arrange financing for the major investment in necessary equipment and know-how, are in the process of making the transition. In Japan, the government is reportedly supplying about 90 percent of the necessary funds. According to Sutherland,[2] use of such techniques could theoretically continue the exponential increase in the number of active elements per chip by another factor of 1,000 and conceivably such chips, computers with 5 megabits of memory, will be available around 1990. It is even conceivable, though one would have to be very greedy to expect it, that the cost will be $10.

COST-EFFECTIVENESS FOR EDUCATION

Let us examine for a moment what doubling the cost-effectiveness of computer hardware every two years could mean for education.

A process that doubles every two years increases by a factor of 32 in one decade. As indicated, we may expect the advance of computer hardware technology to continue for another decade, and, if it does, applications conceived today will go into operation with computer hardware that is 32 times as cost-effective as present computer hardware. That tells us something about what we should be visualizing now as the computer hardware basis for education in 1989 or 1990.

Overall, education is roughly a $50 billion-a-year enterprise with 50 million students. School systems spend, on the average, $1,000 per year per student, almost all of which goes toward personnel and buildings costs. The fact that education is highly labor-intensive must be taken into account when thinking about the near-term future and about transition into an improved regime. By 1990, education could be a $100 billion-a-year enterprise with 100 million students--leaving, on the average, the same $1,000 per year per student, but by that time the balance between labor and technological support could have been adjusted somewhat, and there could be available $200 per year per student for educational technology.

If half of that $200 were spent on computer hardware and if the hardware were amortized over five years, we would be talking about $500 worth of computing equipment per student. In 1988, that equipment might be a 1-microsecond, 32-bit machine with a million bits (32,000 words) of fast memory, plus console and secondary memory; or it might be a share in a larger machine. Either way, it would be an adequate hardware base for very sophisticated educational applications.

The Small Computer

Moreover, as mentioned in the Introduction, large scale integration has already given rise to a range of less sophisticated, inexpensive computers that could be extremely important to education. These computers typically include a processor-on-a-chip, two or more chips for primary

(semiconductor) memory, a keyboard, and a cathode ray tube for display. Often a secondary memory, which is slower than the primary memory but has a considerably greater capacity, is included, and sometimes such a computer contains a modulator-demodulator that permits connection with a telephone. Cost ranges anywhere from $600 for a bare-minimum machine with cassette secondary memory and no modulator-demodulator to several thousand dollars for a machine capable of supporting a small business. The least expensive computers are likely to drop slightly in price in the next year or two, but they are getting near the rock bottom set by the cost of cabinets and marketing. The sector in which further revolutionary improvement can occur is power and capacity at constant cost.

Three configurations of the small computer potentially important to education are:

- A minimal hobby computer, without secondary memory or with only a cheap cassette recorder from which to load programs and data into the primary memory. Currently priced at about $500, this type is unlikely to go much below $250.

- A minimal computer plus a minimal secondary memory, at a present price of about $1,200, which may drop to $500.

- A computer suitable for a small business, with several million bytes of secondary memory, at present about $5,000 and in a few years perhaps $2,000.

Each of these three configurations will become more powerful as time goes on. The first will be useful in educational applications that do not require a data, information, or knowledge base--applications such as monitoring motor skills or testing algorithmic skills. The second class will support applications that concentrate on one lesson at a time and consequently do not require voluminous data. The third class will provide a small but, for many applications, sufficient data base.

The Videodisc

Another item of information technology that promises to become both cost-effective and useful to educators is the "videodisc." A disc will hold 30 minutes to an hour of television program material--video plus audio--and should cost only about a dollar per copy to manufacture in quantity (though it will probably sell for considerably more than that). The playback machine, not including the television set to which the video disc device is attached, is expected--because of its appeal to the mass entertainment market--to sell for only $500 to $1,000.

Half an hour's worth of U.S. television program material equals 54,000 component still pictures, or television frames. The cost could be as low as 0.04 cent a frame. Discs could sell commercially for approximately $10 per disc. Once the discs were paid for, the incremental

cost of disc frames would be only 0.02 cents per frame. For the sake of comparison, consider a textbook page to be the equivalent of four television frames and to cost about 4 cents.

USING INFORMATION TECHNOLOGY TO IMPROVE EDUCATION

The promise of advanced information technology to education lies, not merely in its cost-effectiveness, but also in the opportunities it offers to improve the quality of education. Addressed below are only a few possibilities for tapping the potential of computer and telecommunications hardware in the schools.

1. Computer conducted drill and practice. From work that began in the late 1950's, it is clear that computers can conduct drill and practice efficiently and effectively--and in the process motivate students and trainees. In the coming years, computer-based drill and practice will be inexpensive enough to be used on a massive scale. If vigorously exploited, it could ensure that all students have the basic skills--spelling, typing, handwriting, speech articulation, and vocabulary plus a repertoire of strongly memorized associations--through which, with the aid of other educational techniques, they can then build more complex skills--and knowledge and understanding.

2. Computer Assisted Instruction (CAI). Rising from interactions between "programmed instruction" concepts of the late 1940's and 1950's and digital computers of the late 1950's and the 1960's, CAI has developed progressively through the 1960's and 1970's and can now be evaluated objectively. It has not revolutionized public education or even deeply penetrated this area. But in some military and business applications it has proven both effective and cost-effective. Its use continues to grow and spread as the cost of instructors climbs and the cost of CAI technology falls.

CAI has met with a mixture of overexpectation and moderate success. There are two possible paths for developing it: (1) expand on the patterns of the early 1960's--using compact instructional programs in very inexpensive computers with limited memories; (2) augment the CAI function beyond what was feasible in the 1960's, using powerful computers that are now affordable. The main hope for the first path is that bringing thousands of educators/researchers/programmers into the activity will significantly improve the quality and effectiveness of the software which has in only a few cases lived up to the promise of the medium. The second path is much broader: with the more powerful computers, it will be possible to run much more advanced programs, such as programs that incorporate models of individual students and present ideas in terms of each student's own preferred concepts and analogies. Note that programs can be upgraded progressively, year after year, without attenuation due to forgetting, and that the very best programs--unlike the best human teachers--can be replicated inexpensively and distributed widely.

3. Computer-Managed Instruction (CMI). CMI employs the computer to select instructional topics and materials, schedule presentation and testing, administer tests, and maintain records. At first, the development and use of CMI was largely motivated by the fact that CMI functions were less expensive to perform in the computer than were the instructional functions themselves. Early CMI systems typically did not include direct instructional functions. Now that there is less economic cause to allocate only the least expensive functions to the computer, most large computer-based instruction systems will include CMI along with other instructional functions.

4. Fully computerized instruction. Fully computerized instruction refers to the complete automation of instructional functions. One example of such instruction is the introductory course in logic at Stanford University; the course is so "fully computerized" that no regular meetings are scheduled between students and instructors or assistants. Not many examples of fully computerized instruction exist at the present time; but if it proves feasible in applications for which demand is great, economic forces will surely favor it in the future. Use of fully computerized instruction could result in significant alternatives to schools as we know them--for instance, fully computerized schools with counselors but no teachers; network-based schools with centralized CMI and distributed CAI; on-the-job education and training; and student-managed home study.

5. Use of computers in solving problems. This application of digital information technology to education is the most prevalent. The significance of the pocket calculator to education can be debated, but not the fact of its penetration into education. Moreover, many thousands of high school and college students are now making use of larger digital computers in solving homework problems. Many are becoming acquainted with computer-based text editing and document preparation.

This infiltration of information technology into the lower orders of the educational process should not be written off as trivial or inconsequential. By eliminating the drudgery of numerical calculations and the bother of erasing and retyping, the computer increases the net joy of learning and frees time for the more significant aspects of scholarship.

6. Use of computer and programming concepts to foster discovery and organization of ideas. Computers and their languages give students new approaches to thinking, new ways of dealing with information and knowledge. They also bring a concreteness to otherwise vague or abstract ideas. Computer modeling permits students to concentrate on the parts of a complex concept one at a time and then put the parts together without loss through forgetting. Through graphic display and control of physical objects, the computer can create dynamic, reactive situations for students to explore, and the laws governing those situations can be varied to make it evident to students how the laws influence behavior. For example, the gravitational attraction between the objects in a dynamic model can be made inversely

proportional to the distance separating them, and then to the square of the distance, and then to the cube.

7. Learning in an information-technology-based-environment that gives the student broad scope for initiative. In contrast to the models above, which emphasize the use of computer and programming concepts to foster discovery and learning, this concept emphasizes the student's initiative rather than the teacher's or the computer's.

One can envision a rich learning environment within the computer, a dynamic library, as it were, with text to read on any subject of the student's choosing, with a fuller explanation of every term and concept ready to be called up to the screen by the touch of a stylus, and with models to be set into action and experimented with, and with problems to be solved under the monitorship and guidance of the computer. Surely it will be possible to make exploration in such an environment--an environment matched and adjusted to the capabilities and interests of the individual student--more enjoyable than comic books and television.

However, the development of such information-technology-based learning environments will be a major undertaking. It will not be possible to create such environments simply by providing access through computers to voluminous digital stores of text, formulas, graphs, diagrams and pictures. It will be necessary to develop new information structures of the kind called "knowledge bases" in the current experimentation in the field of artificial intelligence.

If information technology brings about a revolution in education, it will probably be part of a larger revolution in the representation of knowledge. Some of the complex information structures and formal languages that are "natural" to the computer will turn out (after much adaptation through human engineering) to be natural to humans, too. Heretofore, natural languages have dominated man's efforts to preserve and transfer knowledge and have been challenged only on narrow fronts--by the languages of mathematics and the jargons of technical fields. But the computer appears to be bringing us powerful new ways of representing ideas and the relations among ideas, and these new representations may someday be as significant to education as the computer itself.

8. Practice in an information-technology-based environment that simulates a real-world task. A prime example in this category is the computer-based aircraft simulator, used to train pilots. Simulation has also proven valuable for putting business students through the process of making decisions and experiencing outcomes. The importance of simulation to the cognitive side of education is not yet understood; it remains to be seen whether simulation is mainly useful in the development of cognitive skills or whether it can also play a major role in the development of substantive knowledge.

9. Learning by teaching human students in an information-technology-based environment. The observation that the instructor learns more than his students appears to have a special significance in computer-based education. In this approach the computer is interposed between the human instructor, who is himself or herself a student, and the other students, and the instructor makes his or her main cognitive contribution by preparing tutorial programs and/or knowledge sets with which the students interact. It is difficult to prepare a tutorial program or knowledge set without understanding the knowledge it represents. Therefore, asking a student to prepare such a program is an excellent way to teach a concept. Even such a subject as convergence and divergence of series becomes crystal clear and intuitively concrete as soon as one prepares a program that generates and plots series with manually controlled parameters.

This approach will have an additional advantage during the early years of education's efforts to exploit computers: it will help alleviate the inevitably severe shortage of good tutorial programs and knowledge sets. To overcome the shortage, several students could prepare software to teach the same thing, test their products in a balanced and controlled experiment, and then improve them by borrowing experimentally proven techniques from one another.

Eventually, one may argue, all the tutorial programs and knowledge sets will have been prepared, tested, and optimized. At that time, the method may have outlived its usefulness.

10. Learning by teaching computers. The notion of learning by teaching computers differs from the notion of the preceding section only in that the immediate aim is to "educate" the computer rather than human students. The indirect aim is still to educate the teacher, who is a student. This approach need not wait for any fantastic advances in artificial intelligence. Students in Seymour Papert's learning laboratory at Massachusetts Institute of Technology have been learning by programming computers, which can be viewed as "teaching" if the term is taken very broadly. Albert Vezza, also of M.I.T., has been exploring how to design computers to make them amenable to being "taught." If that idea can be developed, it may add a new dimension to learning-by-teaching.

What this topic means practically is the construction of knowledge bases that can be processed by computers. Some progress has been made toward practical, significant knowledge bases in a few areas of medicine (e.g., mass spectrometry applied to organic compounds, selection of antibiotics) and applied mathematics (e.g., simplification of rational polynomials, indefinite integration). An interesting array of techniques has been developed--including semantic networks, relational networks, procedural networks, scenarios, frames, knowledge representation languages, and several techniques based on predicate calculus. Indeed, some of the most impressive demonstrations of artificial intelligence have been made by knowledge-based systems such as DENDRAL,[3] MICIN[4] and MACSYMA.[5]

The preparation of computer-processible knowledge bases for various fields of knowledge might turn out to be the best possible way to develop learning-by-teaching. The aim would be to convert the knowledge of each field from its initial form--text, equation, or diagram, plus whatever the form is inside the heads of people--to the new form selected to facilitate representation in computer memory and processing by computer. The hypothesis is that the byproduct, education of the preparer of the knowledge base, would be extremely valuable, in and of itself.

DANGERS IN THE APPLICATION OF INFORMATION TECHNOLOGY TO EDUCATION

Essentially conservative influences that tend to resist or impede--or igrore or neglect--the application of information technology to education are at present much stronger than either the technological imperative or the driving urge of the field of education to take advantage of every effective means to improve itself. It may therefore seem far-fetched to worry, now, about dangers that may lie in exploitation of information technology to advance education. But it is not too soon to begin systematic study of such dangers. Unintended and undesired side-effects of applications of technology appear to be more ponderous and more difficult to control--and to require more lead time for analysis and understanding --than the intended and desired direct effects. With advocacy of the application of information technology to education, therefore, one should couple advocacy of the development and implementation of policy to guide the application.

Some of the main dangers to be avoided are imaged, though not in very sharp focus, by popular concerns about computers and computerization. Among the prescient fears are that computers will emphasize facts over concepts and principles and that they will be used to promulgate propoganda, to condition uniform acceptance of political doctrines, and to dictate preferences, beliefs, tastes, or philosophies. Although there is nothing in the essential nature of computers that prevents their dealing with concepts and principles or that insists upon a uniform world, there is no doubt that it is easier for stupid people to write programs that deal with facts (or simple non-factual assertions) than to write programs that clarify concepts or that deduce or induce (or even express) principles, and there is no doubt that uniform treatment (by computers or by people, of computers or of people) is cheaper and faster than individualized interaction. Indeed, a large part of the topic of dangers in the application of information technology to education is related to the fact that what is easiest and most profitable to do is, by and large, not at all what should be done in the broadest interest of the society and mankind. The trouble is epitomized by the two senses, the one pejorative and the other not, of the word "exploit." It is important to tackle early the problem of how to take full advantage of the socially desirable educational opportunities offered by the technology (i.e., how to exploit) without letting organizations interested mainly in quick profit (i.e.,

exploit,) ruin the whole prospect with a lot of low quality software that will do unwelcome things efficiently.

There is no way to do justice to the subject of technological threats in a short concluding section. Three mere assertions will have to suffice:

1. Education needs the help of information technology so badly, and the technology is so ready to be adapted to help, that it would be senseless to withhold the help without carefully examining both the opportunities and the threats.

2. Education can be so strong a force, shaping our civilization and our social life, and information technology is so potent in danger as well as in promise, that it would be foolhardy to move full speed ahead in the grasping of opportunities without putting great effort into the analysis of issues and the formulation of policy.

3. Most of the applications that appear to offer strong opportunities and weak threats are difficult applications that will require the development of educational methods and techniques as well as the writing of programs and the collection of data. The applications numbered 6 through 10 in the previous section fall into this category. Work on these applications should be intensified early, along with the policy studies. The applications to hold up until we can see better where we are going are the applications in which a lot of computer hardware would be purchased to run the same few CAI programs coast-to-coast and the applications in which new technology merely puts new faces on old methods--copying existing textbooks on videodiscs, for example, and cutting down the diversity of sources in the process.

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FUNDAMENTAL RESEARCH IN TECHNOLOGY IN SCIENCE EDUCATION

John Seely Brown

The advanced technology game is changing in fundamental ways. In the past, computers were expensive. Now, they are becoming cheap. Such hardware used to be the property of a privileged few; today it is becoming ubiquitous. An older generation will remember computers limited in memory, speed and capability when compared to today's more powerful systems let alone systems currently on the drawing boards.

For these reasons, the fundamental question of educational technology is changing from how to live within restricted computational environments, to how to take educational advantage of the new and revolutionary increase in raw computer power. I believe major research programs are needed to provide answers to this basic question. To be successful, such programs must encourage a fusion of computer science and cognitive science--a fusion well typified by the following set of questions:

- In what form should this new power be delivered; and what kinds of powerful knowledge representation languages should replace the restricted programming and authoring languages of the past?

- How can the tacit knowledge and strategic reasoning of an expert physicist, engineer, and mathematician be modeled on a computer thereby enabling the computer to evaluate a student's conjecture or help him work through a problem?

- How can the computer be developed to serve as a flexible mentor to the student; and what are the criteria for intervening in the learning process at appropriate times? How can we determine the levels and depth of a student's knowledge; or know when too much or too little information and guidance is being provided to the student?

Opportunities for Natural Learning Environments

In the following pages, I will elaborate on some of these concerns that I believe are central to understanding the potential for a computer-based cognitive approach to science education.

Informal Learning Environments

Within ten years the computer will be as omnipresent in the home as television, providing immense opportunities for informal learning in the home. However, if personal computers are used in the future to provide only drill and practice material or "fun and sexy" arcade-style games, much of this potential will be lost. Learning environments must be invented--environments that are simultaneously appealing and educationally significant. This is no easy task.

Examination of the current informal learning environments, such as science museums, reveals the profound and subtle nature of balancing entertainment and pedagogy. Nevertheless, it can be done: each home can literally have its own "science museum," where people can obtain a set of intuitions and experiences that would serve as a cornerstone for understanding formal and basic scientific laws.

Guided "Learning-by-doing" Environments

Radically new possibilities for the computer in both informal and formal learning environments are evolving from the integration of the computer serving as a creative, exploratory medium as well as an intelligent mentor. As a medium, computer-based activities such as turtle geometry, music boxes, simulations, and other special purpose programming systems can provide a wide range of environments for students to explore new concepts. However, such environments also contain many opportunities for students, if left totally on their own, to become "lost" or to form questionable generalizations. But the computer can act as a mentor or coach, and "observe" the use of the medium by the student. It can interrupt students at appropriate times to get them out of ruts or to point out how some aspect of their current activity illustrates an important principle.

The combination of the computer as a medium and as a mentor or coach makes possible guided "learning-by-doing" environments that provide an opportunity for helping a student learn how to integrate factual knowledge with explicit problem-solving strategies. Activity-based tutoring, such as performed by a laboratory instructor, also has the effect of making students more aware of the incomplete state of their knowledge. They learn how to strategically "play" with a partially understood idea--until it is thoroughly mastered or until they can succinctly describe their confusion. Interestingly, such activity-based learning is apt to be attractive, not only to the gifted student, but also to the potential high school dropout.

The Need for Synergism Between Cognitive Science and Educational Technology

From my perspective, the Education Directorate has an unprecedented opportunity to seize the initiative in establishing a powerful synergism between basic research in cognitive science and educational technology. This is especially true of those aspects of cognitive research that provide insights into the underlying skill acquisition and understanding processes involved in mathematics and the sciences.

In the struggle to "tap" the potentials of advanced technology, my own group and those of my colleagues are constantly discovering the need for research into the underlying cognitive mechanism of the "understanding process." This research often requires us to articulate the tacit knowledge and strategies that constitute both common sense reasoning and expert

behavior for a given task domain. The cognitive theories we seek must have a degree of completeness and precision unparalleled in psychology and educational theory, since they must be directly incorporated into instructional systems. Thus, educational application acts both as a powerful forcing function on the development of precise cognitive theories and as an experimental medium for evaluating such efforts. Since theories can be embedded directly in educational systems, they have the additional property of not requiring extensive retraining of teachers before they can be deployed.

Let me provide some examples of what we know about embedding cognitive theories within educational systems. Teaching students problem-solving skills has long been a deep concern within the education community. With the advent of computers, the task of constructing and debugging programs has provided an ideal domain for students to develop their problem-solving skills. Recently, through the combined efforts of the cognitive science and artificial intelligence communities there has been considerable progress in specifying a collection of precise problem-solving and debugging strategies. Once these strategies have been formalized, it becomes possible to explicitly represent them as computer-based problem-solving and debugging assistants that can directly interact with the student while he is solving a problem. This interaction provides the student with personalized, concrete examples of the strategies, as well as showing him how and when to apply them.

One of the best examples of this is a tutorial system: the SPADE programming editor incorporates an explicit (but limited) problem-solving theory of programming in the form of a "planning grammar."[1] This system allows a student to interact with a smart "editor" that uses its theory of problem-solving to guide students in the systematic design of a program. During this process, the computer-based editor can articulate for the student the design choices that must be made and the strategies that can be used to choose between them. While this example is limited in scope, it does point the way for more complex systems.

Such educational systems require a complete representation of all the tacit knowledge required to perform a skill, together with a cognitive theory of how this knowledge is learned, stored, and distorted. With such a representation, it is possible to build an automatic tutorial assistant that can construct an accurate diagnostic model of a student's underlying misconceptions from the symptoms manifested in his work. The same technique can be used to construct adaptive tests that can differentially diagnose a student's misconceptions in an optimal fashion. While we have the necessary representations for arithmetic skills, representations for even slight extensions, such as fractions or high school algebra, are still incomplete.[2] Thus, a great deal more cognitive research is needed for modeling even the relatively well understood and formal domains of mathematics and the physical sciences. However, with the right kind of research, the forthcoming models can yield substantial payoffs in education.

Some Technological Issues

Thus far we have focused our discussion on cognitive issues that must be addressed in shaping a far-reaching research program in technology and science education. There are many novel technological research issues that must also be addressed in order to achieve the kind of synergism between the cognitive and educational technologies necessary for constructing these new learning environments. I will discuss some of these technological issues, ranging from the general, concerning how to make the personal computer a more accessible medium, to the subtle, concerning how to embed domain-specific knowledge in the medium to create "microworlds" for the student to explore at will. This is by no means a complete list of issues that must be considered. It is only intended to be suggestive of various dimensions of this type of concern.

The Machine Has No World View

As previously noted, one of the most obvious and widespread uses of the computer in education today is as a medium for exercising individual problem-solving skills by having students write and debug programs. As computers become more and more pervasive in our society, the issue of how the general public can program computers to perform complex tasks becomes increasingly more serious.

Why is it so difficult to get the computer to do what one wants? Although there are many partial answers to this question, I believe that there is a subtle but pervasive problem that must be considered. Briefly stated: each of us develops communication skills for dealing with other individuals. These skills, in part, amount to developing a model of the hearer's "world view," and then using this model to guide what we say and how we say it. In fact, communication often involves the adjudication between the hearer's and speaker's "world view," until one is certain about what presuppositions are safe to make and what metaphors are most likely to convey the subtleties one has in mind. Communicating with a computer, on the other hand, is quite different.

In some sense the computer has no world view, or at best, a very limited one! Most of our tacitly developed communication strategies are useless on the machine. Not only are we unable to speak to it metaphorically, but in general we cannot count on shared presuppositions (or the adjudication of conflicting presuppositions) to help clarify what we really mean.

What does it take to give the computer a world view? What kind of knowledge does it require to foster flexible communication? For example, how can one embed in the computational medium prototypes of "tools," "concepts," and "design principles" that the user can conveniently modify and extend in order to create his own unique program? It is generally recognized that the design process is the most challenging part of constructing a program. Yet to the best of my knowledge, there is virtually

no research focused on what properties of a computing environment facilitate the naive user in designing his own program (with the notable exception of Alan Kay and Adele Goldberg's efforts, described in his 1977 work).[3]

Programming Assistants for Personal Computers

A related problem is the issue of programming, debugging, and on-line help environments that would provide support to a student constructing his own program. Although there is at least one provocative example of a rich programming environment designed for the expert programmer [see INTERLISP],[4] one wonders what kinds of programming environments would be useful for the student or casual user. Could such environments/assistants radically alter how students learn about and use computers?

Microworlds

Another type of learning environment achievable through future technology is the notion of rich "microworlds," where the computer simulates either a real or hypothetical world, and students get to "fiddle" with the world by running various experiments to discover its structure. The creation and use of such simulated worlds, or "bodies of knowledge," have potentials that have remained chiefly unexplored. How, for example, can we structure a sequence of "microworlds" that reflects a natural evolution toward some final knowledge state? Can such microcosms overcome the time consuming properties and limitations inherent in laboratory exercises, yet still maintain a sense of realism that helps refine a student's intuition of the physical world? Can real bodies of expertise, such as those underlying systems of medical diagnosis, be augmented to create explorable worlds? And, finally, can high performance symbolic mathematical systems that can flawlessly carry out complex mathematical operations, such as symbolic integration, provide environments in which students can develop a deeper understanding of physics by exploring the consequences of their own mathematical models of a situation?

A Cognitive Component to Microworlds

The successful incorporation of explorable, manipulatable microcosms into the student's educational experience requires development of one of the most important cognitive skills: how to use such an environment to develop the student's own ideas or theories. Simply stated, this involves good information seeking strategies, how to go about efficiently seeking information, generating hypotheses, and discovering counterexamples.

Of course these problems are not new. Indeed, by watching the casual library user trying to find out some given piece of information, we can recognize how important, yet poorly developed, such skills are. They will become even more important as our society becomes increasingly dependent on information exchange. The need to discover and precisely represent the skills needed to effectively deal with large information spaces brings us

again to recognize the potential role of cognitive science in education. If these skills can be articulated, and if we can construct computer-based coaches that can watch a student's interactions with these information rich "microworlds," we will be on the verge of a completely new kind of personal learning environment.

Methodological Considerations

In the past, educational technologists have had a relatively good understanding of the potential for easily using a computer, given the stringent computation limitations that had to be placed on each student's interaction with the machine. As I have stressed throughout this paper, these limitations are being destroyed, thereby opening up countless new ways the computer could be used. The promise of tomorrow's technology brings with it visions of glorious learning environments. The real points of leverage that will allow these visions to become realities are, however, very difficult to discern. Many schemes seem intuitively implementable and educationally beneficial. Unfortunately, our intuitions are necessarily based on limited experiences that did not have the benefit of technology.

For example, three years ago my colleagues and I set out to build a computer-based coach to augment the PLATO game "How The West Was Won." We had established that some augmentation was needed in order to achieve the inherent potential of this clever computer-based game. Given the simplicity of the game, we were certain that we could build an "intelligent" instructional system to coach the student on better moves, and thereby expand his horizons. Indeed, building the expert was straightforward, but we had failed to appreciate how much more there is to tutoring than just being an "expert" problem-solver. A good tutor must determine when to interrupt the student and what to say.* To do this, there must be diagnostic strategies for understanding a student's strengths and weaknesses, as well as general coaching strategies for determining good times to interrupt. Without devising and implementing these additional components we were doomed to failure. Without these strategies, the computer-based expert would constantly "hassle" the student to such an extent that he would quickly lose all interest in using the system. Our initial intuitions were quite offbase. We did not realize the subtleties of building an automated coach, nor did we predict the seminal nature of the general paradigm that arose from this effort.

*This is not a trivial point. It is much better pedagogy for the student to discover something for himself. Every time we tell the student something, we are robbing him of the opportunity to discover it. Most human tutors interrupt much too often, generally due to a lack of time or patience and really act more like consultants.

These experiences lead me to suggest two methodological points:

- Powerful computing environments must be constructed that enable research educational technologists to flexibly implement and experiment with prototype systems. Although such environments might be expensive, constraining their tools and research methods to the kind of computers that would deliver the finished product could be far more costly.

- Formative evaluations of new learning paradigms should be encouraged in which the emphasis is placed not on "proving" the educational effectiveness of the given paradigm, but rather on thoroughly characterizing the underlying causes of its strengths and weaknesses.

Truly useful evaluations depend critically on the first point. If one has to invest many years producing a system, one loses both objectivity and the desire to vigorously explore the limitations of the system. However, with the right kind of experimental environment, an individual can make mistakes that add significantly to the understanding of what is important, without throwing away gigantic amounts of work. In other words, just as one worries about cost-effective instruction, one must also worry about research environments that foster cost-effective mistakes!

The Change of Content

Thus far we have focused our attention on the ways in which technology and cognitive science can have an impact on the form of science education. Given the extent of this technological revolution, it surely is going to have an impact on the content of science education as well. The near omnipresence of the computer by the mid-1980's, coupled with the fact that nearly every school age child is apt to have his own programmable computer game system, suggests that the underlying concept of processes, programming, and debugging will be widespread simply through informal learning in the street. Given this assumption, one would expect that the language of algorithms and heuristics will play a dominant role in expressing basic scientific and mathematical laws that are to be taught. For example, the rules for symbolical integration, if taught at all, will be viewed as a set of precise heuristics and strategies expressed in some high-level programming language.

More important, new disciplines relevant to utilizing the new technology will emerge. A trivial example may be the already formulated domain of control theory--a theory that may become as important to students as mechanics. Soon, undoubtedly, students will be hooking up computers to mechanical or external devices and be faced with some serious issues of stability and responsiveness in the control and guidance systems. This, in turn, will lead to interesting new concepts concerning the integration of low-level mathematical control theory with the hierarchical notions of planning in artificial intelligence--all of which will likely become part of high school level science courses by student demand.

Funding

Because of the rapidly changing capabilities of computational and cognitive technologies, and because of the vast amounts of basic research necessary to develop the educational opportunities afforded by the technological revolution, a long-term program must be created for funding the relevant basic science issues. This research is inherently interdisciplinary and may even require the formulation of a new discipline. As a result, the need for quality people, including researchers, faculty, and students, is critical to guarantee that proper foundations are laid. But such rare individuals must be convinced that program money will continue if they are to make a commitment to defining this emerging area. But funding alone will not guarantee success. Indeed the potential pitfalls in the domain are numerous. Unlike nearly any other branch of science, each new technological generation (which seems to occur about every three years) may develop fundamentally new educational paradigms that will not necessarily be appreciated by the inventors of the last great breakthroughs. Special care must be taken, both in the review process and in the organization of this new research community, to ensure that the new "radical" uses are fully investigated.

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TECHNOLOGY IN SCIENCE EDUCATION

Arthur Luehrmann

The potential educational benefits of new information technologies (e.g., television, broad-band communication, and especially the computer) have been widely disseminated in both popular and professional publications. There has also been a recent history of well-funded, well-publicized demonstration projects, a few of which provide evidence that some technologies are cost effective. Yet U.S. education continues, as it has for decades, largely unaffected by these technologies.

The following analysis suggests that the present low level of use of technology in education is the result of fundamental incompatibilities between the U.S. system of education and most of the technology systems intended to perform educational functions. With few exceptions no one has found the way to make such technology part of the educational system. Improvements in cost effectiveness will not change that situation.

For the same reason, active promotion of educational technology systems, especially by Federal agencies, is viewed by the present educational system as an imposition and a threat. The Carnegie Commission report on educational technology is aptly titled "The Fourth Revolution: Instructional Technology in Higher Education." The best known and best funded demonstrations of these technology systems require revolutionary changes in the educational system. The existing system, therefore, must be expected to reject them.

Yet not all technology applications are threatening to our educational system. This paper will be largely directed toward identifying specific places within the existing educational system where some information technologies, especially the computer, are expected to be welcome. These uses of "appropriate technology" have progressed so far on a small scale without much publicity or systematic support. Because they are compatible with the educational system, these relatively neglected applications ought to be given high priority on a Federal research and development schedule during the next decade.

The Nature of U.S. Educational Systems

We can divide the entire system into "school" and "nonschool" systems. The U.S. School system is, by consensus, a very highly decentralized system. Schools depend largely upon local funding and are largely subject to local control. In some states curriculum standards may be established at the state level, but in no case is there a Federally mandated curriculum or defined instructional methodology. At vocational, college and professional levels, the institutions, while larger than pre-college institutions, are even more independent in defining curriculum and methodology.

The nonschool system operates less visibly than the school system, but must be included in this analysis for two reasons. First, it is structurally different from the school system and may be more compatible with information technology systems that are antagonistic to the school system. Second, as people have more leisure time and retire earlier, the nonschool learning environment will be called upon for increased services in such areas as retraining.

The major nonschool environments include the library, museum, job, and home. As places where learning occurs, they are characterized by a relative lack of formal structure, of testing and evaluation, and of methods of providing credit for work done. While it is surely true that more learning occurs outside school than within, it does not result in a transcript of grades or a graduate certificate.

The Federal role in dealing with the school system is well circumscribed. No Federal agency can dictate how or what is taught, but it can undertake programs perceived to be of collective benefit to everyone. Strong pressure exists simply to allocate funds to state and local education agencies for distribution.

The Federal government can respond to national problems, such as the decline in basic skills and the problems of the educationally disadvantaged. It can undertake short-term, "pump-priming" projects, or can sponsor curriculum development where none exists. And it can support research aimed at overcoming the problems of teaching and learning.

The Federal role with regard to nonschool systems may be somewhat less constrained, partly because those systems deal mainly with adults in a non-captive situation. Nevertheless, problems do arise. A nonschool education project must result in a product to be distributed to the intended public. With some important exceptions, public television programs for example, the products are distributed via conventional marketing mechanisms. Ownership problems sometimes arise in these cases when Federal funds have been involved. The more successful the project, the greater the likelihood of Federal embarrassment.

Present Status and Needs of Educational Systems

Perhaps the most salient fact about school systems now and for the next fifteen years is that enrollments are declining. Schools have more rooms, teachers, and administrators than they need. These years will hardly be the best period to introduce labor-saving methods into schools.

One consequence of the disappearance of openings for teachers is that educational change within schools must be accomplished by inservice training of existing professionals and not by putting new courses into the teacher preparation curriculum. While school populations are declining, there is

growing evidence that schools are doing a poorer job of teaching basic skills. They appear to need help in this regard. Furthermore, as they attempt to educate children with a wider range of prior skills, abilities, and attitudes, schools need help in tailoring instruction and testing to the educational needs and development level of each child. In addition, the adult population will have retraining needs and what might be called "recreational learning" needs. As voluntary and forced mid-life career changes occur with greater frequency, people will need additional education. If nonschool environments are used, then new instructional systems will be needed, as well as new organizations.

Greater leisure time and early retirement will generate a demand for recreational learning--learning for the satisfaction of discovery or accomplishment. And for most people, the nonschool setting will be most comfortable.

Appropriate Information Technologies

The technologies which offer the most educational promise are the computer, television, broad-band communication, and combinations of these. The computer is unique among information technologies in that it permits intelligent interaction with the learner. All previous information technologies have been one-way paths for distributing facts and ideas. This is true of printed books, audio recordings, and broadcast or recorded television. The computer alone permits the learner, at his own pace, to interact either with his own efforts--to construct a correct algorithmic representation of a problem--or with a teacher's programmed dialogue. The computer is also unusual in that an individual can learn to use it constructively and creatively as an aid to conceptualizing and solving problems. When a person writes a computer program he is expressing an idea, and when he runs the program he is testing the idea against an expected outcome. Assessment and critical facility are required in testing logic. On a small scale, debugging a computer program is similar to intellectual processes used by researchers in any field. Writing for computers has intellectual dimensions in the same sense that writing essays or solving mathematics problems does.

Until recently, nearly all educational computer uses have been carried out on time sharing systems with per-terminal capital costs of $10,000 to $20,000. Personal microcomputers with similar capabilities cost $1,000 to $2,000 today and will undoubtedly be the preferred technology in the future.

The educational role of broadcast television is well established. It is a one-way medium with excellent cost effectiveness if the product is distributable to a mass audience. On the other hand, high production costs prevent quality programming for specialized audiences. Videotape recording allows "reviewability" and storage, eliminating the need to reach a large

audience at one time. Instead small and specialized groups can be reached efficiently and at the discretion of the communicator. In the end, however, there must be a large audience.

Videodisc recording is more promising than videotape, because reproduction costs are lower, about the same as for reproducing audio records of the same length. It also has the remarkable property of allowing encoding with computer programs and digital data, as well as encoding with pictures and sound. The information on the disc may be accessed in random sequence and read without mechanical wear. In sum, videodiscs have the potential for being a medium for storage and retrieval of complete computer-based educational materials with pictures and sound. Such "intelligent videodiscs" could be used with a personal computer and ordinary TV set as a low-cost learning system in homes, libraries, museums and schools.

Broad-band cable systems have been in use in communities and schools for television and other types of communication. To date, however, the educational effectiveness has been marginal. Nearly all present uses of cable television can be handled more effectively by videodisc distribution, but the spread of personal computers in schools and homes may result in new uses for cable systems, such as the development of information networks.

Direct reception of television signals from satellites may be important during the next 10 years, since it will increase the number of channels available at home, allowing a greater diversity of programming.

Applications of Technologies to Present Needs

Several well known Computer-Assisted Instruction (CAI) projects have demonstrated that computers can be programmed for effective teaching. When dealing with basic skills and special education problems on a remedial level, computers have demonstrated effectiveness at lower costs than traditional methods. Computer use is one component of education cost that goes down each year, and so it is a promising technology for application to many areas of learning. The vast majority of experience with computers in education, however, has not come from such CAI projects.

Instead, and with very little systematic research or development, the computer is gradually becoming a tool that students use as an aid in understanding a wide variety of traditional subjects. In addition, the computer can be used to solve problems, create simulations and models, and to search for data. Education in these uses of computers represents a new and very important need.

CAI, then, appears to address the need for improved effectiveness in teaching basic skills. In addition, CAI naturally lends itself to individualizing and self-pacing, while at the same time being able to carry out the testing and management tasks associated with self-pacing.

Up to now, CAI course material has been developed for the school setting, but the advent of the personal computer will allow CAI materials to be used in many nonschool environments to satisfy some of the needs identified there. Videodisc publication of CAI materials promises the distribution of a very broad range of structured learning material to nonschool environments, although evaluation and accreditation may remain a problem.

In summary, then, broadcast and cable television will have no better role to play in the next 10 years than they have today. Videodisc publication of motion picture material, however, offers a revolutionary opportunity to distribute highly specialized material, including instructional units, directly to individuals, bypassing all institutional middlemen.

It is difficult to foresee how satellite communication directly to rooftop antennas will serve educational needs better than videodisc publication of the same material. Better knowledge of costs is needed.

New Educational Needs Resulting from New Technologies

The new information technologies, especially the computer, have generated entirely new educational needs of great importance requiring a high priority research and development effort. Past large-scale projects have been concerned almost entirely with teaching existing subject matters more effectively and at lower cost. The technology has been viewed merely as a delivery system, and nothing more.

But in the case of the computer, the technology itself contains an intellectual dimension, which has been largely overlooked in major CAI projects. As the computer becomes a part of the home, school, and business landscape, people will need to know how to make intelligent, productive, and creative use of it. There is little doubt that ability to use computers will be judged a basic skill in the near future. Yet there does not now exist a recognized curriculum for teaching computer skills within the school system, or of measuring competency.

These new technology-generated educational needs include: basic education, vocational and professional education, and teacher training.

The basic educational needs are for awareness and for competent use. In a society which increasingly depends on complex automatic information handling systems, it is essential to the democratic principle that the public be aware of the availability, uses and abuses of information and machines that manipulate information. The extent that this "awareness need" is addressed in the school curriculum today--and it rarely is--has resulted in courses that require students merely to read about computers and data networks, without ever experiencing a computer system first hand. The situation is closely analogous to using the oral tradition to teach people about reading and writing. The only acceptable reason for teaching

computer awareness courses without computers has been the cost of equipment. Availability of personal computers has now changed that situation, and awareness courses need to be developed and tested.

More important to basic education than computer awareness, however, is skilled computer use. Consider a person who is able to express understanding of an idea or problem in the form of a prescribed set of instructions, or an algorithm, and is able to write the algorithm as a computer program and run it interactively on the computer. Such a person has a new intellectual tool of basic importance to virtually every subject matter now being taught. Such a person also has a distinct educational advantage over one who does not know how to use a computer in this constructive, analytic mode. Unless the school system provides basic computer skills, the children of affluent families will be the ones who have access to home computers and acquire skills that increase their educational advantage.

Schools, therefore, have need of a basic curriculum in computer use. What exists today is a few isolated instances of unevaluated material, usually in mathematics, designed under the constraint of one or two computer terminals for an entire class, or even an entire school. What is needed is a curriculum for a class in which each student works alone at a computer for about half of the class hours devoted to the course. No curriculum now exists for a "laboratory" course with that amount of "hands-on" experience.

It is also essential that basic computing skills not be identified exclusively with math and science, as they usually are. Experience with students averse to math has shown that they enjoy learning to use a computer and do so effectively when problems are chosen from other fields, graphics and text processing, for example.

Several curriculum development projects are needed in order to explore alternative ways to teach computer skills to different students at different grade and developmental levels. The courses would aim not merely to teach the syntax of a common computer language, but mainly to show students how to perform meaningful tasks, thereby improving their analytic and problem-solving skills. Students would learn to structure problems in a logical form, to express ideas as algorithms, to simulate real systems as computer models, to process text, to construct graphs, and to search data bases among other skills.

Beyond a need for basic computer skills there is a need for vocational and professional training, especially in the field of computer hardware and software. People who can program computers command higher starting salaries within fields with open career paths. A person who knows how to interact with computerized word-processing systems is in high demand now, and that demand will increase along with the growth of office automation.

Present vocational courses in data processing often teach outmoded skills, such as the use of punch-card equipment. Curriculum is needed that is appropriate to the technology expected in the next several years.

Incompatibilities Between Education Systems and Technology Systems

As stated, information technology systems have failed often in education because they are not compatible with existing educational systems. Most information technology systems, for example, require very large initial investment in hardware, software, and courseware. This investment can only be recovered if there is widespread adoption of the result. Schools, on the other hand, are small, decentralized, diverse, and independent organizations accustomed to "cottage industry" production and development methods. They do not buy complete instructional systems: they hire teachers. Teachers are threatened by labor-saving instructional systems.

A new type of organization would be needed to make use of such technology systems and the schools themselves would be threatened by such organizations. If there were a free market in providing basic educational services, economics alone would determine the outcome, as it did in the industrial and agricultural revolutions. But schools are public institutions and part of the political process. Economic factors alone will not bring about an educational productivity revolution.

Nonschool systems--the library, museum, home, job--do not have the same characteristics as the school. They should be more receptive of the benefits of technology-based educational systems. Individuals in their homes, for example, represent a mass market. However, if significant amounts of formal learning are to take place outside schools, then the problems identified earlier, i.e., pacing, testing, giving credit and degrees, must be solved, probably by new organizations.

Some Opportunities for Compatible Systems

Not all educational uses of technology are incompatible with or threatening to the school system. In fact, all of the new educational needs discussed at length earlier are entirely compatible. Satisfying those needs, therefore, is likely to lead to successful adoption of research and development products.

The new courses in awareness and in competent use of computers, for example, would be taught in ordinary schools, by ordinary teachers, meeting in ordinary rooms, using the ordinary class schedule. The only new elements would be the curriculum, the presence of computers, and the teacher's new abilities. All these elements serve the present interests of the schools.

In limited domains, CAI and CMI systems also support school programs. Remedial work is unattractive to most teachers, for example, and CAI systems may be perceived as helpful there, as well as in serving students with special educational needs. Computer management systems may be seen as helpful in supporting individualized self-paced learning and testing.

The nonschool system also provides new opportunities for education through technology systems. Museums and libraries are suitable organizations for offering the public access to information and instruction. Computers can function as "information exhibits," or can be used to guide visitors through a participatory exhibit.

The home also provides opportunities to learn about information technologies. The existence of the home computer will generate a need to know how to make good use of a computer. Videodisc publication permits television and/or CAI courseware to be distributed directly to individuals. New organizations will be needed to produce these materials and to give credit for work done.

Research and Development Priorities

- Basic computer skills curricula. For all of the reasons stated, development of a curriculum for teaching basic computer skills within the school system should have top priority on an R&D agenda for technology and education. It is entirely appropriate for Federal funding because: no other such curriculum exists today; no other organization has sufficient incentive to develop one until a market has been demonstrated; as a demonstration, this curriculum development project is an instance of "pump-priming"; and the need for basic computer skills is national. Several development projects should be funded so that alternative models aimed at different age levels, using different content and methodology, can be developed, evaluated, and offered to schools to choose from.

- Teacher training. In-service training of teachers is needed to assure adequate staffing of the computer skills courses outlined above. Teachers of other courses will also need specialized "subject matter" training to prepare them to apply students' computer skills to learning.

- Curriculum development centers. A critical mass of talented people with experience in teaching students to use computers in a variety of disciplines should be brought together. It is essential that the group be together long enough to work effectively at producing a curriculum in basic computer skills and in the application of computer-based methods to other academic fields. Such a center, to retain its vitality and credibility, would have to deal with actual student populations on a daily basis and would have to employ mechanisms, such as visiting appointments, that assure a steady influx of creative individuals into the development center and return to their teaching environments.

- Community learning environments. Libraries and science museums have served as community learning environments for many years. They are organizationally well suited to providing informal education

to a vast public. A serious effort should be made to expand and intensify their educational role through publicly available computer-based learning systems.

° Development of "intelligent videodisc" personal learning systems. Work needs to be done on engineering problems, authoring systems, record keeping and testing problems, and distribution mechanisms. A demonstration of a working, intelligent videodisc system should precede development of any major courseware activities.

TECHNOLOGY PROGRAM RECOMMENDATIONS

Joseph I. Lipson

Background: Something New

During the 1960's there was considerable ferment and experimentation with the educational uses of telecommunications and computer-aided instruction. For a variety of reasons, including high cost and inadequate course materials, the work did not lead to widespread adoption. Since then the field has changed so dramatically that a call for a new round of Federal attention and support is justified. The reason is two-fold.

First, we are still faced with resistant education problems that labor intensive teaching cannot solve. In particular, the basic skills need extended interaction and practice that newer technologies have shown they can provide. Since the technologies available today are remarkably different, more powerful and less expensive than those of the 60's, a reevaluation is clearly in order. Devices today that cost hundreds of dollars have the computing power that a decade ago would have cost several hundred thousand. The combination of microcomputer and videodisc offers an astonishing array of options including color motion pictures, still pictures, multiple sound tracks, and interactive logic. For the first time the cost of providing information and experience through technology promises to be lower than the print medium. The field is so dynamic that even by the most conservative estimates the devices of five years from now will be amazing by today's standards.

Recent conferences sponsored by the National Science Foundation and the National Institute of Education and Hearings sponsored by the House Subcommittee on Science and Technology have highlighted the new conditions that warrant a renewed look at educational technology. Expert panels have repeatedly called for government attention to the educational potential of the new information technologies. Some of these have included the National Academy of Engineering Advisory Committee on Issues in Educational Technology, Commission on Education; the Carnegie Commission; and the President's Science Advisory Committee. Reports by committees constituting many academic disciplines have made strong and specific recommendations for government support. We judge that these reports failed because they had neither the political or psychological force needed to gain the necessary attention and support. Consideration of the following issues, if combined with compelling demonstrations, should generate the constituency needed.

Economic Position

The United States, with its great industrial strength, can coast for a long time on the momentum generated by its past achievements. However, there are some indicators that may stimulate action by government and legislative bodies.

The United States, the country that developed and applied solid state and electronic technology, finds itself in the position of having almost all radios and television sets being produced in foreign countries. At the present time we are still leading the industry that will dominate the future, the computer industry. Yet Japan and other countries have made clear their determination and challenge. Unless the government, business and universities act together, leadership in the information technologies may be lost in the same way that our position in electronics was lost and our automobile market challenged. For the United States to maintain its position in the computer and computer related industries, the Federal Government should play a catalytic role while still allowing free enterprise to function once markets have been established. In addition, a key factor in the success of any plan will involve the general quality of education, the role of the computer and related technologies in the educational system, and the general levels of computer literacy and use. As in the past, research and development of talent within universities should play a vital role in the process.

Equality of Opportunity

Job opportunities are good, and should continue to improve in careers that require the ability to function with computers and use the information computers provide. This means that equality of career opportunity will become a hollow promise if our educational system reserves computer training and experience for the already affluent. It is essential, therefore, to introduce the new information technologies so that they are available to poor as well as rich. Indeed, more than availability is needed. All segments of society need to become familiar with the technological environment, its power and limitations.

As will be recalled later, computer enhanced learning can also promote equality of educational opportunity. It can contribute to improved motivation and amplify the teacher's ability to offer extended, detailed individualized instruction.

The advent of the computer society implies a continuation of the trend that makes the less-skilled worker obsolete. It imposes the requirement that large classes of workers learn higher level, more complex skills if they are to maintain economic and job security and avoid dead-end careers. For example, manual drafting is now being replaced by computer aided design. Workers who do not acquire skills will be left behind in the dynamic shift of work.

The Opportunity

Federal initiatives that introduce the new information technologies into the educational system will have far-reaching results. Improved educational attainment, intellectual enhancement, increased productivity, and support of the U.S. computer industry are all likely with a relatively

modest federal investment and the history of technological development suggests that the situation is urgent.

We are in a brief, critical period when decisions can assure that the new technologies will serve education. An entire new educational publishing industry, using the computer-related technologies, can be stimulated by Federal attention at a few key leverage points. Federal action to provide authoring facilities, develop new kinds of talent, aggregate the educational market, reduce business uncertainty, and conduct the basic and applied research that is needed can keep America in the forefront rather than the backwash of a knowledge dominated society.

What They Can Do

Eric Ashby called the new information technologies "The Fourth Revolution," a revolution that is comparable to the advent of Gutenberg's printing press. And computing is being recognized as the fourth basic intellectual skill, along with the other three Rs. But beyond these slogans, it is difficult to imagine the range of capability and applications of these image and information machines. Although words are no substitute for a working demonstration, there remain some exciting ways that these devices can be used in science education.

These devices can give people control of space and time. By showing the student new worlds, technology can provide experience that will give an intuitive sense upon which to base more abstract ideas. The computer, through modeling and simulation, will help the student to enter a world in which he must learn in order to explore and master that world. Such applications have far-reaching implications in space technology, as well as the science of genetics. The power of computer simulation, control and change of variables, and the promise of computer prediction offer teaching capabilities never before realized. By programming, the student can function in new and powerful intellectual ways. New images can be created, new models can be designed and tested. For many, the new technologies are the "Dream Machines" predicted by Ted Nelson. One can program and explore the interaction of a complex molecule such as hemoglobin with its surroundings. Programs can move out of the screen with robot devices such as Minsky and Papert's "turtle" that draws pictures as it moves about under the command of a student's program.

In another dimension, the computer and related image devices can also serve underprivileged students, the handicapped, aged and the isolated learner, by providing rich new worlds of drama, color, art, creative effort, and learning.

The Role of the Federal Government

All the available evidence indicates that private enterprise alone will not assure the development of the new technologies for educational purposes.

And, while education is a local responsibility, the Federal Government can not be indifferent to those aspects of education that require a national response: inequality, unemployment, manpower development, national defense, and the educational and research base of industrial development.

Failure of the Federal Government to move swiftly to facilitate educational uses of the new technologies will endanger the economic and, eventually, the military security of the country. If our democratic institutions are to remain stable, we must welcome, rather than fear or ignore, the imperatives of technological change. It is unlikely that we can do this without firmly weaving advanced information technologies into the fabric of our educational system. To accomplish this the public, as well as the schools, need to understand and learn to use these technologies.

To promote orderly and cost-effective development, the panel assembled to consider these issues. We offer the following recommendations, highlighting important leverage points for Federal action in general, and the National Science Foundation in particular.

Recommendation 1: Unique and Accepted Government Functions

We find that there are a variety of activities and functions that are widely accepted and expected of the Federal Government. Properly organized, these can promote intelligent development and use of computer related technologies. Therefore, we recommend that the Federal Government facilitate the development of the new information technologies by decisions and activities such as the following:

- Set telecommunications policy to encourage the proper development and use of the new technologies for important educational purposes.
- Aggregate and stimulate the creation of a new industrial and commercial market through purchasing decisions, equipment subsidies to schools, use of new technologies in government training programs and other mechanisms.
- Undertake an assessment of the impact of these new technologies on the individual, society, education, and our position in the world community.
- Commission periodic measurement of the state of science education.
- Work with other educational agencies to assure that the achievement of students who use the new technologies in novel ways can be properly accredited.

Recommendation 2: New Talent

We find that a severe limitation on the successful educational uses of new technologies lies in the lack of special academic, artistic and

instructional design talent to exploit the new displays and systems. It has been observed repeatedly that the technologies have outrun our imagination and skill in using them. We need to give large numbers of people detailed training and experience with the new technologies.

For this reason, the National Science Foundation should support a variety of programs to discover and develop the new talent needed to exploit the science education potential of the computer and other information technologies.

Recommendation 3: Dissemination

In order to assure the timely, widespread and proper use of the new technologies, including new course materials, the Federal Government should assist in the dissemination of information about them. We find that government activities in this field are already used and trusted. Dissemination activities do not compete with industry and they are relatively inexpensive.

In sum, we recommend that, as a part of a general Federal dissemination effort, the Foundation should develop programs to prepare teachers to use the new technologies in science education, teach computer skills to students, and participate in the development of educational uses of the new technologies. If such a program is not initiated, the new technologies will not reach populations that urgently need them. If we, as a people, are to capitalize on and control the new technologies, the educational system should ensure the broadest possible access to information and education about computing and its implications. The teacher preparation effort should be coupled with a program to subsidize the purchase of computers for schools. Early impressive experiments and demonstrations with microcomputers and new image devices, such as video-cassette and videodisc players, will serve an important dissemination function.

We also recommend a variety of smaller dissemination activities such as a Chautauqua program on the new information machines and their implications for science education.

Recommendation 4: An Informed Public

We find evidence that, only with an informed public, can the nation hope to move into a computer age with the speed and sense of purpose required. The adoption of a new technology as far-reaching as computer technology is incredibly complex. At almost every stage there is strong interaction with public attitudes and public understanding. Investments, markets, legislative positions, enrollment in courses, and selection of careers will all vary with public awareness and knowledge.

We recommend that the Foundation, in cooperation with other Federal agencies, initiate a program using the mass media to alert the public about the issues. In addition, use of specialized media to reach specific publics should be used. Examples include the extension of the Chautauqua

concept to the public, displays in public places and at meetings, and technology based courses for the segment of the public that becomes seriously interested. Mass media elements of such courses have been shown (telecourses, courses by newspaper) to reach a large general audience and so serve to contribute to the mass media program of public understanding. A point to be emphasized is that the educational use of the new information technologies can serve the special groups such as the handicapped and people who need to continue their education while working.

Recommendation 5: Breaking the Software and Course Materials Bottleneck

We find a key bottleneck is the lack of excellent course materials and software. Almost every expert and relevant government official whom we have contacted makes this observation. Furthermore, excellent materials are one prerequisite to the commercial investment in the educational uses of new technologies. Hardware manufacturers are reluctant to develop models with educational features unless there are excellent materials to attract buyers. Conversely, publishers will not invest in the development of materials unless there is an established market represented by large numbers of devices in the schools and in homes. Thus, federal support of development of software and courseware will act as an important catalyst for commercial development. After an initial period of pump-priming the commercial cycle should take over.

We recommend that the Federal Government support the development of innovative materials that allow for future trends in the information technologies. Anticipation of future developments is critical since the field moves so rapidly that projects based only on present capabilities will be obsolete by completion time. We also recommend the funding of key technical developments to facilitate the authoring and production of educational materials. These developments will attract authors and potential publishers and lower production costs. The Foundation should support this development. An approach should propose novel ways of utilizing new technologies and address the problem of teaching procedural competence, as well as the acquisition of knowledge.

Examples of specific projects to be supported include: prototype science course materials; special authoring facilities including computer simulation, electronic editing and production facilities; and prototype student environments that demonstrate the technological features that will soon be available.

Recommendation 6: The Research Challenge

We find that our conceptions regarding the representation and growth of knowledge, understanding and skill, are not adequate for the effective use of today's technology. Current systems have outrun our existing concepts of human learning and human interaction with computer-based environments. Thus we recommend a broad, sustained attack by the Foundation and other agencies on urgent and promising research questions. An active research program will

improve the design of educational environments and experiences, will help us to understand how technology affects human development. It will help us to think about the long range results of our decisions.

Recommendation 7: Equipment Support

We believe a program of carefully designed support for the placement of microcomputer technology into the classroom will complement and make more effective the research, development and dissemination programs recommended. In a sense, equipment demonstration during the early phases of implementation can serve as a model to generate communications about the innovative idea, and provide a compelling demonstration to educators as a whole. Without a federal program, business will have insufficient incentive to enter the field and the new technology will be reserved for the affluent. Computer power in schools should come to be thought of as a utility like water or electricity. We recommend that the Federal Government provide support for the carefully controlled introduction of microcomputers into the schools. The program is needed as an incentive to assure the strength and leadership of the United States in the computer industry.

We recommend that any program of equipment support be tied to evidence that a teacher is trained and committed to the use of equipment, and the school's record of effective use of innovative technology. Costs can be controlled in several ways. Part of the continual decision as to support levels for equipment should be based upon evidence that the support is having the desired effects. Support to each school should provide sufficient numbers of microcomputers to serve a class of students learning to use computers.

Impact

The evidence suggests that a Federal investment in the new information technologies will result in a pattern of increased economic and intellectual productivity and an enhancement of the quality of life. Just as the Federal investment in the land grant colleges transformed agriculture and the quality of rural life, an investment in research and development for the new knowledge environments will, we believe, transform and improve our ability to deal with a constantly changing and challenging world.

Summary: Technology Recommendations

The dramatic change in capability, and the cost of information and image machines will touch every aspect of our personal lives and health as a society. And science education, as broadly conceived by the National Science Foundation, will face a unique challenge in responding to the opportunity. New knowledge and skills can be taught through new forms of learning experience. Concepts and procedures can be more effectively taught to a

wide range of students. For the Federal Government to meet its responsibility in the field of education and for the National Science Foundation to assure the health of science, we recommend the following:

- Use of unique and accepted government functions in meeting national needs, setting telecommunications policy, and providing information that promotes educational uses of new technologies.
- Support relatively low-cost training programs to develop new talent needed by new and expanding technologies.
- Support and participate in the dissemination of information about new technologies, with projects that include programs for teacher preparation.
- Support public information and education about the new technologies through the mass media and other communication approaches.
- Support the development of outstanding course materials for teaching both knowledge and skills through the new environments made possible. The National Science Foundation should be particularly active in the support of prototype software and courseware in the fields of science.
- Support research into basic and applied questions of learning; especially questions raised by the new technologies that these technologies can help answer.
- Support the purchase of computing equipment in order to provide working demonstrations, support the educational technology industry, and provide computer access to those populations that cannot afford it.

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